

Testing the $E_{peak} - E_{iso}$ relation for GRBs detected by Swift and Suzaku-WAM

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April 29, 2009

ABSTRACT

One of the most prominent, yet controversial associations derived from the ensemble of prompt-phase observations of gamma-ray bursts (GRBs) is the apparent correlation in the source frame between the peak energy (E_{peak}) of the $\nu F(\nu)$ spectrum and the isotropic radiated energy, E_{iso} . Since most gamma-ray bursts (GRBs) have E_{peak} above the energy range (15-150 keV) of the Burst Alert Telescope (BAT) on *Swift*, determining accurate E_{peak} values for large numbers of *Swift* bursts has been difficult. However, by combining data from *Swift*/BAT and the *Suzaku* Wide-band All-Sky Monitor (WAM), which covers the energy range from 50-5000 keV, for bursts which are simultaneously detected, one can accurately fit E_{peak} and E_{iso} and test the relationship between them for the *Swift*

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sample. Between the launch of *Suzaku* in July 2005 and the end of March 2009, there were 45 gamma-ray bursts (GRBs) which triggered both *Swift*/BAT and WAM and an additional 47 bursts which triggered *Swift* and were detected by WAM, but did not trigger. A BAT-WAM team has cross-calibrated the two instruments using GRBs, and we are now able to perform joint fits on these bursts to determine spectral parameters. For those bursts with spectroscopic redshifts, we can also calculate the isotropic energy. Here we present the results of joint *Swift*/BAT-*Suzaku*/WAM spectral fits for 86 of the bursts detected by the two instruments. We show that the distribution of spectral fit parameters is consistent with distributions from earlier missions and confirm that *Swift* bursts are consistent with earlier reported relationships between E_{peak} and isotropic energy. We show through time-resolved spectroscopy that individual burst pulses are also consistent with this relationship.

Subject headings: gamma rays: bursts

1. Introduction

The *Swift* gamma-ray burst explorer (Gehrels et al. 2004) mission has vastly increased the number of gamma-ray bursts (GRBs) for which X-ray and optical counterparts have been detected. This has led to a much larger sample of bursts for which a redshift is known or inferred. For the first 409 bursts that triggered *Swift*, 135 have a published redshift, compared to 42 redshifts before the advent of *Swift* (Jakobsson et al. 2006). This data set has allowed for the first time the use of GRBs as cosmological probes (e.g. Schaefer 2007). Once redshifts were known for a significant number of bursts, several authors derived relationships between various measured quantities of the prompt emission – most of these relationships involved relating the time-averaged $\nu F\nu$ spectral peak energy (E_{peak}) of the prompt emission to bolometric properties of the explosion. Testing such relationships for *Swift* bursts using *Swift* data alone is problematic because the narrow bandpass of the Burst Alert Telescope (BAT) (15-150 keV for a strong modulated response; Barthelmy et al. 2005a) is below E_{peak} for the majority of GRBs. Our results show that three quarters of *Swift* bursts have $E_{peak} > 170$ keV. However, when the *Swift* data are combined with data from another instrument with a higher energy response, such as the Wide-band All-Sky Monitor (WAM) on *Suzaku* (Yamaoka et al. 2006, 2009a), it is possible to accurately determine E_{peak} for all bursts which are bright enough for their spectra to be reasonably fitted.

Due to the large fields of view of the Burst Alert Telescope (BAT) on *Swift* (Barthelmy et al. 2005a) and the WAM on *Suzaku*, it is not uncommon that GRBs will be observed

by both instruments. Between August 2005 (the start of the *Suzaku* mission) and March 2009, 45 bursts triggered both instruments. Of these bursts 21 have redshifts. There are an additional 47 bursts untriggered in WAM (and 1 untriggered in BAT), 14 of which have redshifts. After rejecting 7 bursts which could not be fitted, we were able to fit the spectra of 86 bursts. Of this set, 24 bursts were best fitted by a simple power law model (see below for details on the models used), thus we have 62 bursts (28 with redshifts) for which E_{peak} can be determined – about two per month and 20% of all *Swift* triggers (27% of triggers with redshifts) during the period of overlap between *Suzaku* and *Swift*. This compares to 8 *Swift* bursts in the sample reported by Amati (2006, hereafter known as A06).

The first paper in which an energy-fluence relationship was derived using accurately determined burst redshifts was that of Amati et al. (2002). In this paper the authors analyzed twelve GRBs detected by BeppoSAX and derived a linear relationship between $\log(E_{peak})$ and $\log(E_{iso})$, where E_{iso} is the total bolometric energy (1-10,000 keV) of the burst. A06 extended and revised this work using a larger sample of 41 bursts, but found that short GRBs and the subenergetic event GRB 980425/SN1998bw do not fit the main relation. A number of authors have compared *Swift* bursts to these pre-*Swift* relations. Cabrera et al. (2007); Nava et al. (2008) and Ghirlanda et al. (2008) all show that there is no significant difference between *Swift* and pre-*Swift* bursts in terms of E_{peak} relations, although Ghirlanda et al. (2008) caution that spectral analysis threshold effects could influence the correlation for *Swift* bursts.

Ghirlanda, Ghisellini & Lazzati (2004) found that a tighter correlation could be derived if one corrected the total burst energy for collimation using the jet opening angle, which was in turn derived from the panchromatic break time in the afterglow light curve using a geometric relationship (Sari, Piran & Halpern 1999). This is known as the $E_{peak}-E_{\gamma}$ relation. It has been difficult to study $E_{peak}-E_{\gamma}$ relations for *Swift* because *Swift* bursts show more complicated afterglow light curves than had been observed before and a smaller fraction of bursts show clear late-time jet breaks (Panaitescu 2007). However Ghirlanda et al. (2008) found that the relationship derived by Ghirlanda, Ghisellini & Lazzati (2004) ($E_{peak}-E_{\gamma}$) holds for the small sample of *Swift* bursts for which a jet break time was derivable. However, Campana et al. (2007) point out that the presence of significant outliers weakens the case for an $E_{peak}-E_{\gamma}$ relationship. Since the sample of *Swift-Suzaku* bursts with confirmed jet breaks is so small, we do not attempt here to comment on $E_{peak}-E_{\gamma}$ relations.

A somewhat different relationship is derived by Yonetoku et al. (2004) showing a linear correlation between $\log(E_{peak})$ and the log of the luminosity during the peak second of the burst. This relationship has been refined by adding the high-signal GRB time duration (Firmani et al. 2006) or a luminosity time (Tsutsui et al. 2009).

All of the relations discussed above have been criticized by various authors. In particular, Band & Preece (2005) and Nakar & Piran (2005) show that the majority of BATSE bursts are inconsistent with both the $E_{peak}-E_{iso}$ and $E_{peak}-E_{\gamma}$ relations, and Butler et al. (2007) argue that the relations are mostly due to selection effects. We show in this paper that the $E_{peak}-E_{iso}$ does hold for long *Swift* bursts, and that the association cannot result simply from selection effects.

The organization of the paper is as follows. In §2 we discuss methodology and data selection and describe the spectral models used. Then in §3 we describe the distributions of spectral fit parameters. In §4 we cover the correlations between burst parameters and compare these results to previously published results. Finally, in §5 we provide general conclusions and interpretation.

2. Methodology

All of the bursts used in this study triggered either the Burst Alert Telescope (BAT) on *Swift* or the Wide-Band All-Sky Monitor (WAM) on *Suzaku*, and in nearly half the cases triggered both instruments. The spectra were fitted jointly to the BAT and WAM data and fits include the time-integrated spectra and sets of time resolved intervals as described below. Either one or two of the four WAM detectors were used in the fits, depending on which of the side detectors were hit. For all but one of the BAT bursts¹, event data were used to derive first a light curve in the 15-200 keV band. From this light curve we used the standard *Swift*/BAT tool `battblocks` to determine the total time interval of the burst in the BAT energy range, T_{100} , and those subsidiary peaks of the prompt emission which were found by the tool to be statistically significant. The `battblocks` tool uses the Bayesian Block method of Scargle (1998) to determine significant time intervals in a light curve based on Bayesian analysis. The initial Bayesian blocks are determined from the BAT light curves, but we elect to combine blocks so that they represent significant variations in both BAT and WAM. The bin edges are then shifted to match the time quantization of the WAM spectral data (see below). The normal *Swift* response to a GRB consists of a spacecraft slew to the burst location commencing usually between 7 and 40 seconds after the trigger and lasting typically between 40 and 80 seconds. For 37 of the bursts in the sample, the prompt emission which was intense enough to be analyzed in both BAT and WAM lasted into the spacecraft slew and for 24 of these bursts, the prompt emission continued after the termination of the slew.

¹The one exception is GRB 060124, for which BAT triggered on a precursor. This event is discussed below.

Since the location of the burst in the BAT field of view (FOV) changes during the slew, care must be taken when deriving the instrument response for bursts containing slews (see below). For this reason, we have also divided burst intervals into, as appropriate, pre-slew, slew and post-slew periods and when Bayesian block edges fall within a few seconds of the start or end of a slew, we have shifted the bin edges to match these physical transitions.

For each significant time interval, we used the tool `batbinevt` to derive a BAT spectral file and `batdrngen` to derive a response file. When the spacecraft pointing was stable (pre-slew and post-slew) we could use a single response file since the burst was at a constant position in the FOV. For any intervals overlapping in whole or in part with the slew, we used a special procedure to average the response so that it correctly accounted for the changing location of the burst in the FOV. This procedure is described in Sakamoto et al. (2008a, hereafter known as S08). Sakamoto et al. (2009b) have shown that there is no systematic problem with analyzing the BAT spectra data during the slew using a weighted energy response. Tables 1 and 5 indicate clearly which bursts and burst intervals are so affected.

The temporal boundaries of the selected *Swift*/BAT intervals had to be further adjusted to match the WAM data. The WAM spectral data have a time quantization of 0.5 seconds for BST data covering the period from 8.0 seconds before to 56.0 seconds after a burst trigger, and 1.0 seconds for the TRN data outside these intervals and for untriggered bursts². Thus the boundaries of the time intervals must be adjusted to match the WAM time quantization. Times were also corrected for time-of-flight differences between the two spacecraft, but because both are in low-earth orbit, this correction is typically only a few milliseconds. The WAM data were inspected for each of the BAT-derived time intervals and when WAM emission was intense enough for a spectrum to be derived, a WAM spectral file was produced. In a number of cases it was necessary to combine multiple BAT time intervals into a single interval in order to get enough WAM counts for fitting. Since *Suzaku* only rarely slews during bursts³, a single response file for each WAM detector is used for a given burst. In several cases, even though two WAM detectors were hit, it was decided to use only one WAM detector for analysis, either because the incident angle was bad (passing through too much passive material) or because the count rate was too low in one of the detectors to allow a proper spectrum to be accumulated. Such cases are noted in Table 1.

Suzaku WAM data analysis was performed using the standard FTOOLS in the HEADAS

²The current setting for WAM BST data was initiated on March 20, 2006. Before this date, all WAM spectral data have 1.0 second time resolution.

³The only GRB in our sample for which *Suzaku* was slewing during a burst was GRB 070721B. We were unable to fit a spectrum to this burst, so it is not included in our analysis.

version 6.6 package. In accordance with *Swift*/BAT time intervals, the spectra were accumulated and deadtime corrected. The WAM instrumental background is significantly variable with time, so we fitted the WAM light curve for each channel before and after the time intervals with a 4th order polynomial function, then interpolated the best-fit model into the source extracted regions. The energy response was calculated based on incident angles using the response generator, *wamresp*gen. The energy range was limited to be above 120 keV in the fitting. Uncertainties of the flux using the current response is estimated at about 30% above 120 keV (Yamaoka et al. 2009a).

For each time interval, joint fits were made to the BAT and WAM data. Data were fit using *xspec*11.3⁴ to a simple power law (PL) model, a power law model with an exponential cut-off (CPL), and the two-component (Band) model (Band et al. 1993). The functional forms of these models are, respectively:

$$N_{PL}(E) = C \cdot A \left(\frac{E}{E_{norm}} \right)^\alpha \quad (1)$$

$$N_{CPL}(E) = C \cdot A \left(\frac{E}{E_{norm}} \right)^\alpha \exp \left[-\frac{E(2 + \alpha)}{E_{peak}} \right] \quad (2)$$

$$N_{Band}(E) = \begin{cases} C \cdot A \left(\frac{E}{E_{norm}} \right)^\alpha \exp \left[-\frac{E(2 + \alpha)}{E_{peak}} \right] & E < E_c \\ C \cdot A' \left(\frac{E}{E_{norm}} \right)^\beta & E \geq E_c \end{cases} \quad (3)$$

In each of the above equations, A is the normalization in photons $\text{s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$, E is the energy, measured in keV, E_{norm} is the normalization energy, which is fixed at 100 keV for this analysis, α is a photon spectral index, and C is a dimensionless constant. In the Band model, β is a second photon spectral index, $E_c \equiv (\alpha - \beta) \left(\frac{E_{peak}}{2 + \alpha} \right)$, and, the normalization parameter A' is defined as

$$A' \equiv A \left[\frac{(\alpha - \beta) E_{peak}}{E_{norm}(2 + \alpha)} \right]^{(\alpha - \beta)} \exp(\beta - \alpha) \quad (4)$$

In the fits, the constant C was fixed to a value of 1.0 for the BAT and was allowed to vary as a free parameter for the WAM. The fits for each interval and each model were inspected and a time interval/model was rejected if either (a) the lower-energy power-law index, α , was

⁴<http://heasarc.gsfc.nasa.gov/xanadu/xspec/xspec11/index.html>

not constrained, (b) the reduced chi-squared, $\chi_{red}^2 > 2$ or (c) the WAM constant C was not consistent with unity (with a few exceptions listed below). For the CPL and Band models we added the criteria that (d) E_{peak} be constrained. We do not require the higher energy index β to be constrained. If the original “total” time interval did not yield an acceptable fit, then a shorter time interval which was better matched to the extent of the WAM emission was chosen for the time-integrated interval. Such cases are clearly noted in Table 1. In the subsequent discussion the term “total burst interval” will designate the longest continuous time interval over which an acceptable model fit can be made to either the CPL or Band model. In a companion work (Sakamoto et al. 2009b), the cross-correlation between BAT and WAM (and also Konus-*WIND*) is studied in detail. They find that the normalizations between the instruments are consistent to within 20%.

For each time interval (time-integrated and time-resolved), the “best” spectral model was determined. The default for each case was a simple power law model. If, however, the difference in χ^2 between the PL fit and the CPL fit or between the CPL fit and the Band fit was $\Delta\chi_{(a,b)}^2 > 6.0$, where $\Delta\chi_a^2 \equiv \Delta\chi_{PL}^2 - \Delta\chi_{CPL}^2$ or $\Delta\chi_b^2 \equiv \Delta\chi_{CPL}^2 - \Delta\chi_{Band}^2$, then the more complicated model was deemed to be the “best” model. Of course this more complicated model fit also had to meet the acceptability criteria listed in the preceding paragraph. With this selection method, for the full burst intervals, 26 bursts were found to be best fit by the simple PL model, 48 by the CPL model and 12 with the Band model⁵. However, for all of the bursts for which the CPL model was the best fit, the Band model was also an acceptable fit. In each case the values of E_{peak} for the two models were identical to within statistics.

In all cases in which either the CPL or the Band model is the best fit and for which a redshift is known, we then transformed E_{peak} to the source frame by multiplying $E_{peak}^{observer}$ by a factor $(1+z)$. The next step was to determine, for each burst, the isotropic energy, E_{iso} , integrated over the total burst interval and over each time-resolved burst interval. To make sure that we were comparing equivalent quantities for each burst, we used only the Band model to calculate the integrated flux, including those cases for which the Band model gives an acceptable fit, but is not the “best” fit model. This choice is justified in §3. We also include in our sample bursts for which the high energy power-law index β is not constrained, allowing the uncertainty in this parameter to contribute to the overall error in the flux. To find E_{iso} , we used the definition of Amati et al. (2002) to derive E_{iso} from the integrated flux: $E_{iso} = 1/(1+z) \int_1^{10000} [EN(E)dE \times 4\pi * dL^2]$. To allow direct comparison we used the same cosmological parameters as the earlier authors: $H_0 = 65$ km/s, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

⁵In two cases, GRBs 050915B and 081190A, neither $\Delta\chi_a^2$ nor $\Delta\chi_b^2$ were > 6.0 , but $\Delta\chi^2 = \Delta\chi_{PL}^2 - \Delta\chi_{Band}^2 > 6.0$, so these bursts are included in our data set and E_{peak} values used in the analysis.

It is also important to check the results for overall quality of fits. In Figure 1 we show two plots which verify the overall validity of our results. In Figure 1a, we show the distribution of reduced χ^2 for the time integrated and time resolved fits. We see that both histograms peak at $\chi^2_{red} = 1$ with an appropriate distribution of values. In Figure 1b we show a histogram of the WAM normalization factor for those bursts and sequences which otherwise meet the quality standards outlined above. We see that the distribution has a peak at unity as expected, but also a tail at high values of the normalization constant. Two of the tail points in the time integrated histogram at just above 4.0 are due to GRB 060124, which is a unique burst in the sample in that BAT triggered on a precursor ≈ 450 seconds before the main emission and the WAM trigger. The BAT event data extended to only $T_0 + 302$ s, where T_0 here and henceforth refers to the *Swift*/BAT trigger time. Therefore, we used BAT survey data with a time resolution of 250 seconds instead of the usual $100\mu\text{s}$ resolution. The WAM data covered only the 33 seconds of actual emission. This difference in data duration is responsible for an increased WAM normalization factor. Since the energy resolution for survey data is as good as for event data and the analysis looks robust, we include the burst in our sample. The other high tail point is due to GRB 080218A, which has a very low $E_{peak} = 32 \pm 9$ keV, and for which E_{peak} is fitted well with the BAT data alone. Inclusion of the WAM data does not significantly affect the result, so given the high normalization factor, we have decided to report the result of the BAT fit for this burst. Tail points for individual sequences were from weak sequences and were excluded from the data tables and plots.

3. Results of Spectral Fits

The results of this analysis for individual bursts are given in four tables. Table 1 gives a list of all jointly detected bursts and includes BAT and WAM trigger numbers, the WAM detector sides used in the analysis, BAT T_{90} , and the temporal extent of each total burst interval. In Tables 2 – 4, the fit parameters for the total burst intervals are given. Bursts for which either the CPL or Band models are acceptable fits are listed in Table 2, while those bursts for which only a PL model is acceptable are listed separately in Table 3. Table 4 lists the fluence values from a Band model fit for each burst in Table 2. Finally in Table 5 we list the fit parameters for each time-resolved burst segment for which we could find an acceptable fit to either the CPL or Band model. We do not include burst segments for which only a simple PL is an acceptable fit.

Histograms of the fit parameters for the time integrated and time resolved spectra are shown in Figures 2 – 6. The figures are organized first by parameter: the low-energy power-

law index α in Figures 2 and 3, the high-energy power-law index β in Figure 4, and E_{peak} in Figures 5 and 6. For a given parameter a pair of plots (time-integrated and time-resolved) is given for each model that contains that parameter. In other words, the α parameter is plotted for all three models, the β parameter only for the Band model, and the E_{peak} parameter for the CPL and Band models. Each histogram is created by accumulating a point for each spectrum in which the given parameter is constrained for the given model, regardless of whether the given model is the best model for that spectrum. For example, GRB 051221A is best fitted by the Band model – however, α is constrained for both the PL and CPL models, so it contributes to the histograms in all three of Figures 2a, c, and d. In contrast, GRB 051006 is best fitted by the PL model, while the α parameter is constrained for the CPL model, but not constrained for the Band model – this burst only contributes to Figures 2a and 2c. To make it clear whether best fits or acceptable fits contribute, each plot has two overlaid histograms, the solid one representing the best fits and the dashed ones the acceptable fits. For this purpose a parameter is considered constrained if *xspec* is able to provide error bars on the parameter that are not pegged at either the high or the low end of the parameter space searched. For the time integrated spectra we also show the histograms of the parameters distributions for short bursts in blue⁶ The median values and the dispersions (quartile) for each histogram are given in Table 6. We also show a set of scatter plots in Figure 7. We plot E_{peak} and α with respect to fluence in the 1–10000 keV band, and α versus fluence in the 15–150 keV band. We also plot E_{peak} with respect to α . These plots are discussed in the text below.

In Figures 3a and 7c and the first column of Table 6, one can see clearly that the best fit to a burst depends strongly on the power-law index α . In contrast, Figure 7c shows that the nature of the best fit model does not depend strongly on burst fluence. By scanning across Figure 3a we note that the harder the burst (more negative α) the more likely we are to be able to fit a model with a larger number of parameters. For the softest bursts (green histogram in Figure 3a), only a PL fit is acceptable. Then as we move to the right in Figure 3a ($\alpha \approx -1.2$; red histogram), we find that most bursts are best fitted by the CPL model: as the low-energy index hardens, there is enough fluence in the WAM band to be able to find a spectral break. For the apparently hardest bursts (dashed black histogram), the Band model fits best.

For the time resolved spectra (Figure 3b), the bias toward lower α for best PL fits is also seen. Furthermore, in examining Figures 3c, 4c and 6c and the relevant individual histograms, one can see few differences in the distributions of α , β , and E_{peak} between time

⁶Note that the solid black histograms are cumulative, including both long and short bursts.

integrated and time resolved fits. One can see in Figure 3c that the median α for the time resolved spectra is softer than that for the time integrated spectra. The time resolved spectra are more likely to be from later and hence softer segments of the bursts.

Although there are far fewer short bursts than long bursts, one can see some differences between spectral fit parameters for these two classes of bursts. In Figure 3c, we note that although the distributions overlap, short bursts are clustered toward the hard side of the α distribution, with a median value, -0.72, different from the overall median, -1.23. Figure 6c gives a similar picture – one cannot distinguish short from long bursts by their E_{peak} values, but short bursts are much more likely to have a high value of E_{peak} than are long bursts.

3.1. Power Law Spectral Fits

First we examine the bursts for which the PL model is the best fit. One can see clearly in Figure 7c (black points), that these are not intrinsically faint bursts, even though we are likely “losing” a significant fraction of the flux below 15 keV. However, due to their spectra, these bursts tend to be very weak in the WAM band and/or have an E_{peak} value below the WAM energy threshold and a weak “lever arm” in the BAT energy range, so that it is not possible to fit a spectral break using the joint BAT/WAM data. The basic conclusion of this is that if the low-energy index $\alpha \gtrsim 1.5$, it is very difficult to constrain E_{peak} with the BAT-WAM data unless the burst is particularly bright ($F > 7 \times 10^{-6} \text{ erg/cm}^2$). As the work of Sakamoto et al. (2009a, hereafter known as S09) shows, bursts in this range tend to have low values of $E_{peak} \lesssim 100 \text{ keV}$. Figures 7a and 7b show that there is no apparent correlation between burst fluence and the form of the most acceptable spectral model.

The results of S09 allow us to verify that E_{peak} for the PL-only bursts is indeed likely to be within the BAT energy range, but below the WAM energy range. In Table 3 we include estimates of E_{peak} derived from the formulas given in S09 which relate E_{peak} to the power-law index derived from a power-law model fit, α (called Γ in S09). Two of the bursts (GRBs 060211A and 060322) were bright enough to be fitted with the BAT data and we have used E_{peak} from S08. Another two bursts have α outside the range for which the S09 formulas are considered valid and we report no E_{peak} values. For 19 of the 22 bursts with E_{peak} values we see that our best fit estimates of E_{peak} are within the BAT energy range, but below the WAM energy range. All of the remaining three have E_{peak} values at the lower end of the WAM range and PL indices near the lower edge of the validity of the S09 relation, so E_{peak} values derived from S09 may be in question. GRB 080303 and GRB 090305 are weak bursts which were not triggered in WAM. The other, GRB 080123, did trigger WAM, but we were unable to constrain E_{peak} with either the BAT-WAM data or the BAT only data. However,

with a few possible exceptions, all PL-only bursts in our sample have estimated E_{peak} values in the BAT energy range which puts them at the low end of the BAT-WAM energy range.

In conclusion, for this set of bursts we are fitting mostly to the part of the Band spectrum above the break energy. Therefore what we derive as α in a PL fit is actually β in the intrinsic spectrum, hardened somewhat by an inclusion of part of the spectrum above the break. This explains why the PL index values are so hard ($\alpha \approx -1.6$).

3.2. Cut-off Power Law Spectral Fits

Next we examine those bursts for which the CPL model is the best fit. In those cases for which E_{peak} is determined, one can see an interesting trend in Figures 5c and 7d. Bursts for which the Band model is statistically favored tend to have a hard $\alpha \sim -1.0$, but a *low* $E_{peak} \sim 80$ keV (solid histogram in Figure 5c and blue points in Figure 7d.). Beyond this set, we find a large sample of bursts (dashed histogram in Figure 5c) for which the Band model is an acceptable fit, but not statistically favored over the CPL model. For these bursts, one finds a much broader distribution of E_{peak} values with a higher average $E_{peak} \sim 300$ keV. What this tells us is that for most bursts with a moderate $E_{peak} : \sim 100 < E_{peak} < 1000$ keV, *both* the Band and CPL models produce acceptable fits, but only for those bursts with particularly low E_{peak} , is there sufficient flux above the spectral break that the Band model is favored by more than $\Delta\chi^2 > 6.0$. We can see from Figure 4a and the fourth column of Table 6 that most of the bursts which are “Band-acceptable/CPL-favored” (*BACF*) have a distribution of the high energy Band parameter β quite similar to the “Band-best” bursts. For these bursts, we are fitting mostly to the part of the Band spectrum below the break energy, where a cut-off power law dominates. An inclusion of part of the spectrum above the break softens the apparent α . Some of the bursts in the *BACF* set do have β values outside the main distribution ($\beta \lesssim -7$), suggesting that we are only deriving an upper limit for β values for these bursts.

3.3. Band Spectral Fits

Even with the extended energy range of BAT and WAM, we have a minority of bursts for which the Band model is unambiguously the best fit. Earlier studies of burst spectra have shown that the form of the fit model which yields the lowest χ^2 depends where E_{peak} falls with respect to the high and low energy bounds of the detector. In particular Band et al. (1993) show through simulations that even when the Band model is the intrinsic spectrum of

a burst, increasing the lower energy bound in the fit biases fits toward simpler models. They also show that on average fits to bursts with low signal-to-noise (S/N) ratios yield the correct fit parameters, but that the dispersion in the fit parameters increases with decreasing S/N. Later work by S09 show that it is difficult to fit bursts with low E_{peak} with a CPL or Band model because there is not sufficient data on *both* sides of E_{peak} to adequately constrain a model with a break. In short, the results of Band et al. (1993) and S09 tell us that while all bursts are probably representable by the Band model, simpler models are often found to be acceptable or even statistically favored. The distribution of fit parameters and the nature of the best fit models found in our work is consistent with these conclusions.

In §2 we noted that we will use parameters derived from the Band model for the correlations to be examined in §4. Thus it is important to verify that the E_{peak} values derived from the Band fit for the *BACF* bursts are acceptable to use. We conclude that this is the case for several reasons. First of all, as discussed above, spectral studies and simulations show that the Band model is likely to be able to represent all long GRB spectra. Secondly, all bursts for which a CPL model was the best fit could also be acceptably fitted with a Band model. Thirdly, in Figure 5a, we see that the distribution of E_{peak} values derived from the CPL model and the Band model are nearly identical and have median values that agree to within error (see Table 6). Finally we find in Figure 8 that the correspondence between the two E_{peak} values (CPL and Band) is very good. We do see a clear trend for the CPL model to find a higher E_{peak} than the Band model for a given burst. This makes sense if we assume that the Band model represents the intrinsic spectrum: fitting such a spectrum to a model without a separate high energy component requires a higher cut-off energy to adequately fit the high energy data. This is to be expected based on an examination of the functional forms of the two models (Equations 2 and 3) we see that the models are the same for $E < E_c$, differing only in their behavior when $E > E_c$. And using the median values for α and β , we get $E_c \approx 1.3E_{peak}$. As we will see in §3.4 (Figure 9), the BAT/WAM E_{peak} distribution matches the BATSE distribution in the center. These correlations indicate to us that it is acceptable to use Band-model derived E_{peak} values (and E_{iso} derived from a Band model) for bursts where the Band model is acceptable, though not necessarily favored by the χ^2 test. We only include bursts for which we have a good *fit*, not just an estimate of E_{peak} – therefore we do not include in our $E_{peak} - E_{iso}$ plots, bursts for which estimated E_{peak} values are listed in Table 3. It turns out that neither of the bursts in Table 3 with fit E_{peak} values have measured redshifts.

3.4. Comparison to the BATSE Sample

In Figure 9 we compare the best values of model fit parameters to the BATSE results of Kaneko et al. (2006, hereafter known as K06). In Figure 9a we see that the best distributions of the low-energy index α have very similar distributions for BAT/WAM and for BATSE. The BAT/WAM distribution is skewed toward slightly lower α values and has a median of -1.23 ± 0.28 , compared to -1.14 ± 0.21 for BATSE. The BAT only sample contains only bursts that can be fitted with a CPL or Band model and as expected it has a softer α distribution as is expected since only soft bursts can be fitted with BAT data alone. Similarly, as shown in Figure 9b, we see that the high-energy index β has a very similar distribution in the BAT/WAM and BATSE samples. The median values are identical to within error: $-2.23^{+0.12}_{-2.00}$ for BAT/WAM and $-2.33^{+0.24}_{-0.26}$ for BATSE.

In Figure 9c, the best value of E_{peak} for this sample is plotted along with the best values from the BATSE results of K06 and the bursts from S08 for which a CPL or Band model can be fitted. We see that although the medians of the BATSE and BAT/WAM distributions are consistent, the BAT/WAM distribution has larger wings at both the high and low energy ends. The high energy wing is consistent with the larger effective area above 300 keV in the WAM as compared to BATSE (Yamaoka et al. 2009a). This allows us to more effectively fit bursts with $E_{peak} > 300$ keV. The low energy wing is attributed to the lower threshold of BAT compared to BATSE, leading to more triggers on bursts with $E_{peak} < 100$ keV. Although the BAT/WAM distribution is wider than the BATSE distribution, the median values are quite comparable. For this sample, the median E_{peak} is 291^{+283}_{-119} keV, compared to 251^{+122}_{-68} keV for the BATSE sample. We note that our results are consistent with BATSE results even though we include many more faint bursts. The inclusion criterion used by K06 is $F(\sim 20 - 2000 \text{ keV}) > 2.0 \times 10^{-5} \text{ erg cm}^{-2}$. Our sample (see Figure 17b) includes bursts down to $F(15 - 2000 \text{ keV}) \approx 2.0 \times 10^{-6} \text{ erg cm}^{-2}$. This tells us that the fit parameters are not affected by burst fluence.

The “BAT only” histogram has a very different distribution which results from the narrow energy range of the BAT. Only bursts with $15 \text{ keV} < E_{peak} < 150 \text{ keV}$ can be fitted with the BAT data alone. Although the parent distribution is still rising at 150 keV, it becomes more and more difficult to fit a Band or CPL spectrum to the BAT data alone as E_{peak} increases.

4. Results of Correlations

4.1. Comparison to Previously Published Relations

For 28 of the *Swift*/*Suzaku* bursts in the study set, we have a measurement of both E_{peak} and a spectroscopic redshift. For these bursts we can compare the parameters derived in this work to the results published by A06, Campana et al. (2007) and Cabrera et al. (2007).

In Fig. 10 we plot the “Amati relation,” showing E_{peak} versus E_{iso} . In this plot we have included the original A06 data points, with *Swift* bursts in the A06 sample shown in green and other bursts as black diamonds. We have also added other *Swift* bursts for which E_{peak} and E_{iso} have been derived by other authors (Campana et al. 2007; Cabrera et al. 2007); these points are indicated by filled black squares. The bursts from the BAT/WAM sample are indicated by red filled squares (long bursts) and blue filled triangles (short bursts). The black lines are taken from A06, the red line is the fit to the BAT/WAM long burst sample⁷ and the green line is our fit to all *Swift* long bursts shown in the plot. For clarity Figure 11 shows only the long bursts which are neither sub-energetic nor classified as X-ray flashes.

In comparing the bursts from this sample to earlier published samples, two things are apparent. First, there is a relative dearth of bursts in this sample at the lower left of Figure 11 (weak, low E_{peak} bursts). We attribute this to not being able to fit BAT-WAM bursts with $E_{peak} \lesssim 100$ keV, as discussed in §3.1. Secondly, we see a slight excess of bursts above and to the left of the main distribution (weak, high E_{peak} bursts). This is significant and is discussed further in §4.2.

As other authors have, we find that the data are best fitted by a power-law relation, $E_{peak} = kE_{iso}^m$. Following the discussion in A06, we find that χ^2 is reduced if we include an additional parameter σ_v in the fit to account for intrinsic scatter in the data, beyond what can be accounted by simple statistical error bars. The log-likelihood density function P that we maximized is identical to the Equation 5 in Guidorzi et al. (2006), with our parameter K replacing q in Guidorzi et al. (2006). In this function, there is a dependence on the parameter σ_v in the normalization of the log-likelihood distribution, so we cannot simply interpret $\log P = -\frac{1}{2}\chi^2$. If we examine the original likelihood function (Equation 52 and discussion following in D’Agostini (2005)), we see that the exponential part of the likelihood corresponds to the normal χ^2 which is multiplied by a normalization. Therefore, to provide a comparison between the goodnesses of fit for different samples, we quote χ_{red}^2 in the last column of §7 as the minimization of the exponential part of the likelihood function divided

⁷The fit and the discussion in the next three paragraphs excludes the outlier GRB 060505; see below.

by the number of degrees of freedom in the fit.

The results from fits to various parts of this data set are given in Table 7. In the first nine rows, we fitted various data sets shown in Figure 11 to the power-law relation $E_{peak} = kE_{iso}^m$. The first line gives our fit to the original GRB sample of A06 (excluding X-Ray Flashes). We derive a slope m , intercept K and sample variance σ_v consistent with A06. The next three lines are fits to burst samples previous to this work. We see that there is a significant difference between the fits to the 6 *Swift* bursts in the A06 sample and the 33 non-*Swift* bursts, with the slope of the fit to the *Swift* bursts being much higher (0.74 *vs.* 0.43) and the intercept being much lower (55 *vs.* 111). Although the correlation is good ($\rho = 0.94$) and χ_{red}^2 very close to one, the small sample of A06 *Swift* bursts may be an anomaly.

The comparison between the current sample and the earlier sample of *Swift* bursts (lines 4 and 5 in Table 7) is quite close. The intercepts are consistent to within error, although the sample variance σ_v is a good deal larger for the current sample. Neither case shows a great deal of correlation ($\rho \approx 0.73$). One does see a difference between the *Swift* samples and the set of non-*Swift* bursts in the A06 sample. While the slopes are consistent, the intercept is significantly higher for *Swift* bursts and there is a greater sample variance and lower correlation in the *Swift* sample. This tells us that we are now sampling a different part and a broader section of the burst population than did earlier experiments. A higher value of K means that a burst with a given E_{peak} in the source frame will have, on average, a lower E_{iso} . With $m = 0.43$, for a given E_{peak} , E_{iso} for a *Swift* burst would be ($\sim 0.3 - 0.6$) E_{iso} for a pre-*Swift* burst. However, examination of Figure 10 shows that we are actually sampling roughly the same range of E_{iso} as the pre-*Swift* sample, but with a broader distribution of larger E_{peak} values. Despite the differences between the *Swift* and pre-*Swift* sample, like the earlier samples, the current sample shows a clear correlation between E_{peak} and E_{iso} for long GRBs. The points (accounting for sample variance) are best fitted by the line $E_{peak} = (182 \pm 22)E_{iso}^{0.50 \pm 0.04}$, where E_{peak} is in units of keV, and E_{iso} units of 10^{52} erg. This shows that even with a slightly different (higher E_{peak}) distribution, the $E_{peak} - E_{iso}$ relation still holds.

In order to study any possible bias in our data, we have compared our E_{peak} values to those independently derived from bursts which also triggered the *WIND*/Konus instrument (Aptekar et al. 1995). The results for 18 bursts that triggered both BAT/WAM and Konus are plotted in Figure 12. For 12 of these bursts (shown as diamonds in Figure 12), Sakamoto et al. (2009b) matched exactly the time interval quoted by Konus in the literature to a corresponding time interval in the BAT and WAM light curves, and so were able to calculate E_{peak} values that could be directly compared to the Konus values. For these bursts we use the Sakamoto et al. (2009b) values in the plot and in the fits. For the other 9 bursts (triangles

in Figure 12), we do not have the precise relative timing information with Konus, so we show E_{peak} values from this work as close in time as possible to the Konus times. These bursts are shown on the plot for comparison, but are not included in the fits.

Fitting a straight line to the data (dashed line in Figure 12) gives $E_{peak}^{Konus} = (19.5 \pm 8.1) + (0.89 \pm 0.05) * E_{peak}^{BAT-WAM}$, $\chi^2 = 7.8$ for 10 d.o.f. This is formally 2.5σ away from the line $E_{peak}^{Konus} = E_{peak}^{BAT-WAM}$ (solid line in Figure 12). A weighted mean of the ratio $E_{peak}^{BAT-WAM}/E_{peak}^{Konus}$ (dominated by GRB 060117, the point at the lower left with very small errors) is 0.9 ± 0.24 , and without weighting the mean is 1.1 ± 0.24 . The straight-line fit suggests a small ($\sim 10\%$) bias toward larger E_{peak} values for BAT/WAM compared to Konus, and both calculations of the mean of the ratios are consistent with unity and inconclusive as to a systematic bias toward higher or lower $E_{peak}^{BAT-WAM}$. This tells us that if there is any bias in our analysis, it is small and as shown below does not significantly impact our results. Sakamoto et al. (2009b) have found a 10-20% systematic bias in the BAT normalization with respect to KW. However, if we increase E_{iso} values by a random percentage within this range, we do not see a significant change in $E_{peak} - E_{iso}$ fit parameters.

We also examined whether the shift of the $E_{peak} - E_{iso}$ line toward higher K is a redshift effect, since *Swift* is sampling from a higher redshift distribution than earlier samples (Jakobsson et al. 2006). Such evolution was suggested by Li (2007), although Ghirlanda et al. (2008) do not confirm the Li (2007) result. Consistent with Ghirlanda et al. (2008), we do not see any bias with regard to redshift (see Figure 13) and no sign of evolution of the slope or the intercept of the $E_{peak} - E_{iso}$ relationship with redshift (Figure 14). We also fitted the entire set of published *Swift* E_{peak} and E_{iso} values, and find a result consistent with that for our sample, $E_{peak} = (170 \pm 15)E_{iso}^{0.43 \pm 0.03}$. The basic result is that when all bursts are taken into account, a clear $E_{peak} - E_{iso}$ relationship still holds, but the scatter in the distribution is wider than has been previously reported. This makes it particularly difficult to use this relationship to determine pseudo-redshifts, given only the E_{peak} of the burst.

There is one peculiar outlier in the BAT/WAM long GRB sample that is not included in the fit. This point, red at the upper left of the plot, is GRB 060505 (Yamaoka et al. 2009b). This subluminal GRB triggered WAM and passed the first rate trigger stage in the BAT, but it was too weak to trigger the BAT onboard burst response. However since the burst duration was only 4 seconds, the 10 seconds of event data (collected for such “failed” triggers) allowed us to derive a BAT position and spectrum. Although no supernova was found corresponding to this burst location, it is possible that this GRB is similar to another subluminal event, GRB 980425/SN 1998bw, which is located to the far left of Figure 10 at $E_{peak} = 55$ keV, $E_{iso} = 10^{48}$ erg. In order to shift GRB 060505 and GRB 980425 to the right on the plot until they reached the red fit line, we need to multiply E_{iso} for each burst

by a factor of ≈ 1000 . Although more such bursts will need to be studied to verify this, it is possible that GRBs 060505 and 980425 are examples of a separate class of underluminous GRBs with E_{peak} values within the range of "normal" long bursts, but isotropic energy values three orders of magnitude lower than would be expected from the main $E_{peak} - E_{iso}$ relation.

As has been seen by previous authors (e.g. A06), short GRBs do not follow the $E_{peak} - E_{iso}$ relation. These bursts are all outliers to the relation in the direction of lower E_{iso} for a given E_{peak} . If we include GRB 050709 from A06, we can make a tentative fit to the short burst distribution, deriving a fit to $E_{peak} = (1429 \pm 238)E_{iso}^{0.53 \pm 0.07}$, but this fit is heavily weighted by this single burst, while all other short bursts are in a broad cluster for which no correlation is found. And even with GRB 050709 we calculate a correlation factor of only $\rho = 0.24$. Thus we cannot claim that there is any significant $E_{peak} - E_{iso}$ relation for short GRBs.

Another important relation was discovered by Yonetoku et al. (2004), who found a good correlation between the time-integrated burst E_{peak} and the luminosity in the brightest one second of the burst, L_{iso} . We do not examine this relationship in the current work, but given its importance, we will investigate it in a later paper.

4.2. Other correlations from this work

Since we have fits to a great number of individual burst pulses we can compare E_{peak} and E_{iso} for individual burst pulses. This result is shown in Figure 15. The best fit to this sample is $E_{peak} = (332 \pm 11)E_{iso}^{0.43 \pm 0.01}$, which is shown by the solid red line in Figure 15. On the whole this distribution shows a tighter correlation (and less sample variance) than does the time-integrated sample (see Table 7), indicating that the $E_{peak} - E_{iso}$ relation is intrinsic to burst pulses. The slope of this fit (0.43) is consistent with the slope of the fits to the full burst samples, telling us that the full burst $E_{peak} - E_{iso}$ relation arises from a superposition of burst pulses, each of which fit the relation. The offset of this distribution from the time-integrated fit is easily understood. Burst pulses have a distribution of E_{peak} values similar to time integrated E_{peak} values (see Figure 6c and Table 6), but since the durations of pulses are shorter there is less integrated flux in a pulse. Because a total burst is made up of a compilation of pulses, each with its own point on the $E_{peak} - E_{iso}$ plot, it is not surprising that the time integrated distribution has a larger intrinsic scatter. This shows that the total burst $E_{peak} - E_{iso}$ relation is a consequence of the relation holding for individual burst pulses. Using a different relation, Firmani et al. (2009) also find that burst pulses follow the same correlations as full bursts.

It is interesting to ask whether there is any time evolution of the $E_{peak} - E_{iso}$ relation within bursts. To study this we divided the burst pulses into three bins according to when they occurred within the burst. The total duration of each burst (T_{100}) was divided into quarters and the mid time of each pulse was placed into one of three time bins according to whether it was in the first quarter of the burst, the second quarter of the burst or the second half of the burst. The results are shown in Figures 15 and 16. In Figure 16, pulses are colored according to their time bin. There is scatter in all distributions, but we can see some clear differences in the distributions. The earlier sequences (red) have a higher E_{peak} distribution and tend to be clustered in a region of high E_{iso} . As line 10 in Table 7 shows, there is poor correlation between E_{peak} and E_{iso} for this group, which is also evident in the very flat fit line. As the bursts progress the $E_{peak} - E_{iso}$ correlation becomes stronger, and the fit line steepens to match that of the full distribution of sequences (and full bursts). Comparing the 2nd quarter and 2nd half sequences, we see a roughly constant slope, but a drop in the line intercept showing that E_{peak} falls (successive peaks soften) while E_{iso} covers the same range in the two groups. This result suggests that along with the well-known softening of bursts with time that the $E_{peak} - E_{iso}$ relation for burst sequences also evolves with time, with little correlation early in the burst and more later on. As for the time-integrated sample, short burst pulses are outliers to the overall relationship. There are not enough short burst pulses to be able to say whether or not there is any correlation in this sample.

Since we see a correlation in the source frame, it is important to ask whether a similar correlation exists in the observer frame. When the redshift is known, transforming E_{peak}^{obs} to E_{peak}^{source} is effected by simply multiplying E_{peak}^{obs} by $(1+z)$. The transformation from observed flux to isotropic flux is given in §2. There is a factor of $(1+z)$ in the denominator, but since the luminosity distance L is directly proportional to redshift, the net effect is that $E_{iso} \sim z * F(obs)$. Thus to first order both E_{peak} and E_{iso} should scale from observer frame quantities by a similar factor of z .

Therefore in the absence of evolution with redshift we would expect to see a correlation between E_{peak}^{obs} and measured fluence. This relationship is plotted in three frames of Figure 17 for, respectively, fluences in the 15-150 keV (BAT) band, 15-2000 keV (BAT/WAM) band, and 1-10000 keV (extrapolated) band. In each case the fluence was calculated by fitting the data to a Band model, allowing the total area under the curve between the low and high energy bounds to be a free parameter. The exception was the BAT only bursts (green points in Figure 17a, where the fluences are taken from S08). In each plot bursts with and without redshifts are distinguished as are bursts which were detected in the BAT only (Figure 17a). First of all we see no systematic bias between bursts with and without known redshifts (red and black points, respectively), in any of the plots. This tells us that bursts with redshifts sample well the total distribution of bursts. The other important conclusion is that we do

not see nearly as strong a correlation in the observer frame as we do in the source frame. This is not surprising for the plots of fluence in the two relatively narrow bands (15-150 keV and 15-2000 keV) since here we are not capturing all of the burst fluence. However, even when we extrapolate the fits to the same energy range that was used in calculating E_{iso} (1-10000 keV), we still see a much weaker correlation in the observer frame than we do in the source frame. The correlation coefficient in the source frame is only $\rho = 0.47$, compared to $\rho = 0.72$ in the observer frame. Also the intrinsic scatter in the data is higher, $\sigma_v^{obs} = 0.32$ and $\sigma_v^{source} = 0.28$.

We can use Figure 17c to understand this result and compare it to those of other authors. Two sets of lines have been added to this figure. The red lines are based on a conversion from the red best fit lines in Figure 10. Since the fits shown in Figure 10 are based on calculations made in the source frame, it is not a simple matter to transform the best fit lines to the observer frame. Since there is no indication of redshift evolution in the relationships we must take into account the broad scatter in both the ratios $r_1 \equiv E_{peak}^{source}/E_{peak}^{obs}$ and $r_2 \equiv E_{iso}/F$. The first ratio is simply $1+z$, with a median value of 1.51 for this sample. The second ratio, r_2 , is more complicated and is best investigated empirically. In Figure 17d we plot r_2 with respect to redshift. The ratio r_2 covers about 1.5 orders of magnitude, with a median of 6×10^5 in the chosen units. We have used the median values to scale the solid red (best fit) line from Figure 10 to Figure 17c. To scale the dashed lines (3σ limits) we use the extrema of r_1 and r_2 as scale factors. From this scaling we recognize that a narrow relationship in the source frame can accommodate a much broader relationship in the observer frame. In fact we see in Figure 17c that almost all of the data points, both with and without redshift are consistent with the observer frame relationship. This is in sharp contrast to the result found for the BATSE data sample (Kaneko et al. 2006; Band & Preece 2005) in which it was determined that a large fraction of bursts were inconsistent with the relationship in the observer frame.

The two solid black lines on Figure 17c are placed to represent the envelope of points in the E_{peak} – Fluence plane shown in Figure 4 in Ghirlanda et al. (2008). Comparing to these lines (which are approximate) we see only one outlier in the bottom right (low E_{peak} , high fluence), but a number of outliers in the upper left (high E_{peak} , low fluence). These outliers correspond to the points above and to the left of the main distribution in Figure 11. This is the region that Ghirlanda et al. (2008); Butler et al. (2007) and others have discussed as being due to instrumental threshold effects. And in fact this is a region that is excluded in the arguments of Ghirlanda et al. (2008) for *Swift* alone, because *Swift*/BAT alone cannot determine E_{peak} in this region. However, by including an instrument with a much broader energy range, we can extend the threshold into regions that have not been previously explored – not by *Swift* alone because of its narrow energy range and not by other

experiments because of their relatively poorer sensitivity. The relative sparseness of this region for other instruments is understandable: *Swift* is more likely to trigger on bursts with higher fluence and lower E_{peak} .

But the most important point to note is that even these bursts outside the earlier thresholds are fully consistent with the $E_{peak} - E_{iso}$ relation when transformed to the source frame. The result that the E_{peak} – fluence relationship becomes narrower when transformed into the source frame $E_{peak} - E_{iso}$ relationship suggests that the source frame relationship has a physical basis and is not just a reflection of an artificial observer frame relationship. Recently Butler, Kocevski & Bloom (2009) have developed tests for determining whether selection effects significantly affect apparent GRB correlations. We will study and apply these tests in a later paper.

5. Summary and Discussion

We present here a complete set of time-integrated and time-resolved spectral fits for the prompt emission for a set of 86 bursts, 34 of which have measured redshifts. This provides a very useful addition to the *Swift*/BAT catalog (S08), an expansion of previous compilations of bursts for which both E_{peak} and redshift are known (A06; Cabrera et al. 2007; Campana et al. 2007), and a companion to the *CGRO*/BATSE spectral catalogs (Preece et al. 2000, K06). This work shows the power and utility of joint fits with *Swift*/BAT and other instruments with larger energy ranges and we hope that this work will give guidance to future joint fits efforts, such as between *Swift*/BAT and *Fermi*/GBM and LAT.

The main benefit of extending spectral fits beyond the limited BAT energy range is that we are much more likely to cover enough of the spectrum to be able to determine the peak of the $\nu F\nu$ spectrum, E_{peak} . In the majority of BAT/WAM bursts we are able to constrain E_{peak} in either a CPL or Band model fit – those bursts for which only a PL model is an acceptable fit tend to be particularly soft bursts, for which the peak energy falls below the WAM band and hence WAM cannot help constrain the fits. Another great advantage of studying bursts with *Swift*/BAT and *Suzaku*/WAM is that a far greater percentage of *Swift*-detected bursts have measured redshifts compared to previous missions. This means that we are able to determine not only E_{peak} , but also an estimate of the isotropic radiated energy, allowing us to study $E_{peak} - E_{iso}$ relationships in detail.

We are able to show that an $E_{peak} - E_{iso}$ relationship holds for long GRBs, with the possible exception of sub-energetic bursts such as GRB 980425 and GRB 060505. The slope of the fit to our data matches that derived by other authors such as A06, even though we

probe a burst distribution with a higher range of E_{peak} values than have previously been studied. While a full study of possible evolution of the relationships is beyond the scope of this paper we see no sign (Figures 13; 14) that the relationships depend on burst redshift. Although we show a clear correlation between E_{peak} and E_{iso} , the large scatter in the distribution makes any use of this relationship to determine a pseudo-redshift problematic. As has been seen before, short GRBs are outliers to the $E_{peak} - E_{iso}$ relationship, having E_{peak} values in a comparable range with long GRBs, but a short burst will typically have $\approx 100\times$ less energy than a long burst of comparable E_{peak} .

It is also important to compare our results with those from other missions. We first compare our E_{peak} distribution with that of BATSE (K06; see Figure 9). We find that, while our distribution has wider tails, the median values of E_{peak} for BATSE (251^{+122}_{-68} keV) and BAT/WAM (291^{+283}_{-119} keV) are the same to within error. The comparisons of other spectral parameters are similarly within error of each other (see §3.4). As do K06, we do not see any clustering in the low-energy power law index at any values other than ~ 1 . We also make a direct comparison between our derived values of E_{peak} and those from the *WIND*/Konus experiment (Figure 12) and see that the two sets of values agree to within errors.

With the addition of our bursts, there are now a total of 57 *Swift* long bursts and 90 total long bursts for which both E_{peak} and redshift are known. In comparison to earlier E_{peak} relationships, our sample has a higher range of E_{peak} values and a larger sample variance than does the A06 sample, nonetheless, we are able to derive a reasonable correlation between E_{peak} and E_{iso} with a slope that matches that of A06 (0.50 ± 0.04). Similarly we can show good correlations between E_{peak} and E_{iso} for both (a) *Swift* long bursts and (b) all long bursts despite the sample variances, and can fit slopes to the relationship ($m_{(a)} = 0.43 \pm 0.03$ and $m_{(b)} = 0.43 \pm 0.02$) that are consistent with earlier findings. It is important to note that the slope of the relationship is consistent even though the E_{peak} range (reflected in the K intercept parameter) is significantly higher for the *Swift* sample ($K = 170 \pm 15$) than for the pre-*Swift* sample studied by A06 ($K = 111 \pm 7$). Furthermore we confirm that this relationship holds for *Swift* bursts over ~ 3 orders of magnitude in E_{iso} and nearly ~ 2 orders in E_{peak} and over a redshift range of $0.09 < z < 6.29$ with no indication of any variation in the relationship with redshift. We have now shown that the correlation between E_{peak} and E_{iso} holds for a large sample (~ 100) bursts observed by six different experiments and that while the region of $E_{peak} - E_{iso}$ space explored is different for different experiments, the degree of correlation and the slope of the relationship holds constant.

As other authors have found, we do not see a similar relationship for short bursts which show a large scatter and very poor correlation. All short bursts lie in the part of the $E_{peak} - E_{iso}$ plane at high E_{peak} and relatively low E_{iso} . This is consistent with the observa-

tions that short bursts are sub-luminous with respect to long bursts and a further indication that short bursts form a physically distinct population. Also we see that sub-energetic bursts (GRB 060505 in this sample and GRB 980425/SN 1998bw in the A06 sample) also form a separate population from the long burst population, though it is of course not possible to constrain a correlation with only two data points. Like GRB 980425, GRB 060505 is relatively nearby ($z = 0.0894$), but unlike the earlier burst, no supernova has been found associated with the burst. A06 also mention a third possible member of this class, GRB 031203, also nearby ($z = 0.105$) and also inconsistent with the main relationship, although they note that there is particularly large uncertainty in E_{peak} for this burst. Ghisellini et al. (2006) point out that another nearby ($z = 0.033$) event associated with a supernova, GRB 060218, is consistent with the $E_{peak} - E_{iso}$ relation. They go on to show that strong spectral evolution in the other outliers may have meant that E_{peak} could have been much lower and E_{iso} somewhat larger than what was measured, meaning that these bursts might not be outliers. In short, we need more sub-luminous nearby GRBs to determine conclusively whether such bursts do form a separate population of outliers.

Our sample does not contain any X-Ray Flashes, because such bursts would be too weak in the WAM energy range to be detected by WAM. Also, too few *Swift* bursts have solid jet breaks for us to comment on collimation-corrected relationships (e.g. Ghirlanda, Ghisellini & Lazzati (2004)) that involve the jet opening angle.

For the first time we are able to confirm that the $E_{peak} - E_{iso}$ relation holds not just for entire bursts but for statistically separable sub-intervals (sequences) within bursts as well and in fact we find the same slope, $m = 0.43 \pm 0.01$ for sequences as for whole bursts. The intercept K is significantly higher because, as discussed in §4.2, sequence have E_{peak} values covering the same range as entire bursts and with a comparable median (Figure 6c and Table 6), but since their durations are shorter, there is less total isotropic energy. Also we see that the fit parameters α, β and E_{peak} have nearly identical distributions for sequences as for whole bursts. This result that sequences have similar energetic properties to whole bursts is an important result because it shows that with regard to at least this particular set of prompt emission properties, sequences behave just like whole bursts, or conversely, that long GRBs can be modeled as superpositions of individual burst events, each of which has energetic properties similar to a whole burst. Since there is often considerable spectral evolution within bursts and across sequences, it is useful to study individual burst sequences where there is less time for spectral evolution to smear out burst properties. We also see signs of time evolution of the pulse $E_{peak} - E_{iso}$ relationship.

We find a weak correlation with a great deal of scatter between E_{peak} in the observer frame and observer frame fluence F . The correlation becomes much narrower when working

in the source frame which supports the idea that the source frame correlation has a physical origin and is not just a reflection of a narrow observer frame correlation. The union of *Swift*/BAT with *Suzaku*/WAM extends the instrumental threshold of either experiment alone to include more bursts with relatively high E_{peak} and low fluence. But even these bursts which are outliers to earlier observer frame relationships are consistent with the source frame relationship. When we compare bursts with redshifts to bursts without (Figure 17c) we see that non-redshift bursts are interspersed with redshift bursts, hence all of the BAT/WAM bursts are in a region of $E_{peak} - F$ space to be consistent with the $E_{peak} - E_{iso}$ relation, further supporting the interpretation that the relationship is real and not an artifact of a selection effect. This is in contrast to what was seen in the BATSE data (K06; Band & Preece 2005; Nakar & Piran 2005) where a substantial fraction of bursts were found in regions of $E_{peak} - F$ space which were inconsistent with the Amati et al. (2002) relation.

The large, homogeneous sample of bursts presented here gives us an unbiased picture of the energetic properties of bursts detected by *Swift*. The addition of spectral information from *Suzaku*/WAM allows full fits to be made to nearly all of the bursts, and we show that this sample is consistent spectrally with the much larger set of BATSE bursts (K06). Since so many *Swift* bursts have measured redshifts, we are also able to confirm that one of the most important empirical relationships of GRB prompt emission, the correlation between E_{peak} and E_{iso} , holds for our sample. We have shown the validity and importance of combining *Swift*/BAT data with data from another experiment. Since all instruments involved are still functioning, in future years it will be possible to expand the BAT-WAM catalog, and carry out similar joint fits between *Swift*/BAT and *WIND*/Konus and *Fermi*/GBM.

H.A.K. and T.S. are supported by the *Swift* project. This research is supported in part by a Grant-in-Aid for Science Research (19047001 KY) of the Ministry of Education, Culture, Sports, Science and Technology (MEXT). We appreciate the helpful communication with C. Guidorzi about using the log likelihood function for our fits.

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